DEPARTMENT OF THE AIR FORCE
HEADQUARTERS UNITED STATES AIR FORCE
WASHINGTON 25, D. C.

10 January 1963

MEMORANDUM TO MEMBERS OF THE SAB AD HOC COMMITTEE ON SPACE RADIATION EFFECTS

SUBJECT: Transmittal of Information

1. As per agreement reached at the meeting of the Committee held in The Pentagon on 13 December 1962, forwarded herewith for your information and perusal is one copy each of the following:

a. Design and Packaging for Nuclear Exposure, by Dr. Glenn L. Keister

b. Basic Effects of Nuclear Radiation, by J. R. Crittenden

c. Effects of Nuclear Radiation on Electronic Materials, by Dr. V. R. Honnold and Dr. C. W. Perkins

d. Nuclear Blast Effects on Components & Equipment, by Louis L. Kaplan and Richard G. Saelens

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Nuclear blast effects on electronic equipment outside of the heat and blast zones can be overcome. Methods such as shielding, component replacement, circuit design, and advanced circuit concepts can be used to make the equipment radiation resistant. The problem can be attacked in the same manner as for thermal or vibrational environments.

Design and Packaging for Nuclear Exposure

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THE design and packaging of electronic equipment for operation in a nuclear environment can be considered no different than the design for thermal or vibration environments. To provide a reliable design, the designer needs only the information on how the electronic equipment reacts to the nuclear exposure and a suitable means for including this in the design of equipment.

The available techniques to reduce the effects of radiation on equipment are:

1. Shielding from the radiation environment.
2. Replacement of vulnerable components.
3. Circuit design and packaging concepts which reduce the effect of a nuclear environment on circuit operation.
4. Advanced circuit design concepts which allow the circuit designer to more fully understand the interaction of radiation with the circuit and optimize the design of his circuit for a particular nuclear environment.

Several aspects of these various methods will be discussed and examples given of their effectiveness.

Shielding

Shielding, to reduce the radiation environment, is most effective for those radiations which interact strongly with bulk material. As was indicated by Crittenden,[1] the reduction of the intensity of charged particle radiation, such as occurs in space, can be accomplished with much less massive shields than for neutrons or gamma rays of the same energy. Low energy charged particle space radiation can be simply shielded against for most applications. A thin quartz shield plate on space satellite solar cells can extend the life of the solar cells by months or years. This depends on the satellite orbit and the equipment power demand. Fig. 1 shows the mass of material in grams/cm^2 that is penetrated by protons of a given energy. As is seen, a layer of quartz 1 gram/cm^2 thick will stop protons of 40 Mev energy, which is typical of protons that are found in the Van Allen radiation belts.

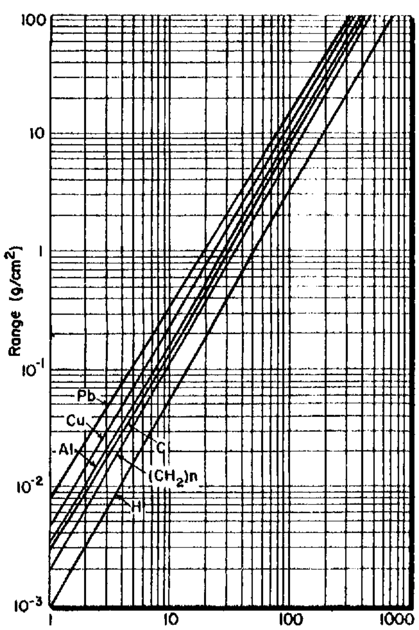
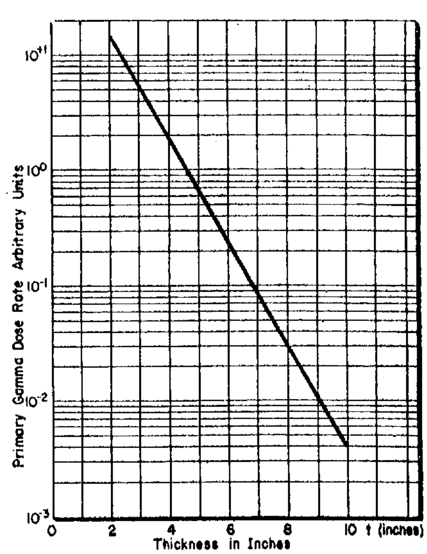
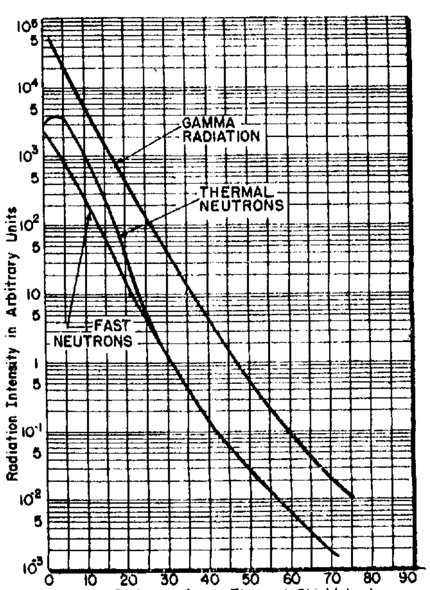


Fig. 1 (l.) Range-energy curves are shown for protons in several different materials.
Fig. 2 (below): Primary dose rate versus lead shield thickness in water media.
Fig. 3 (r.): Neutron and gamma intensities in barytes concrete shield of BEPO reactor.





To shield electronic equipment from neutrons or gamma rays, it is necessary to use much heavier and thicker slabs of material. The need for such shielding is generally associated with the protection required for equipment working near a nuclear reactor or nuclear weapon detonation. Assuming the spectrum of gamma rays and neutrons associated with the fission reactions, the reduction of gamma rays as a function of distance in lead is shown in Fig. 2. Since it is difficult to separate the neutrons and gamma rays from a fission reaction, the neutron and gamma intensity in a typical reactor concrete shield is shown in Fig. 3. For an order-of-magnitude reduction in the neutron and gamma radiation flux, a considerable mass of material is required. This type of shielding is generally only practical for ground-based installations, or where it is necessary for equipment to work near a reactor in an aerospace vehicle, such as a nuclear rocket or nuclear-powered satellite.

Some consideration has been given to the shielding provided by the components themselves. As is seen from the above, it is easy to use component configurations which will shield against low energy electrons and protons. However, shielding against gamma rays, neutrons, or high energy protons is much more difficult, and only if large volumes of equipment, fuel, or food are used could this be done. Many novel shielding concepts have been proposed for space vehicles. Most of these concepts depend on multipurpose use of shielding material.

Component Replacement

One common method of building equipment, which will withstand a nuclear environment, is to replace those components which are susceptible to nuclear radiation and retain those components which are not. Often this type of design technique can be used to construct electronic equipment which will withstand fairly large amounts of radiation. Fig. 4 shows some of the tolerance ranges for electronic equipment that is susceptible to permanent damage. Damage results from atomic displacements caused by fast neutron bombardment.

The reader is referred to the articles in this series[1, 2] for a discussion of interactions of radiation with material and radiation units. In Fig. 4 the cross-hatched area shows where the components are affected but still can be used. The solid line indicates where the component is damaged beyond use. The letters on the right side of the chart indicate the reliability of the information. "A" indicates good design information, "B" indicates partial design information, and "C" indicates fragmentary information. Fig. 5 shows the components which are susceptible to ionization type damage or total absorbed energy. Fig. 6 shows those components which are susceptible to the radiation dose rate or flux. This type of effect is generally thought of as transient radiation which is related, in many instances, to nuclear weapon detonations. The same letter code is used on Fig. 5 and Fig. 6, except on Fig. 6 an arrow indicates the onset of the transient radiation effect.

From these figures we see that many of the components are quite susceptible to radiation whereas others are quite resistant, and that an order-of-magnitude savings in the radiation tolerance can be obtained by selecting the proper components. A good

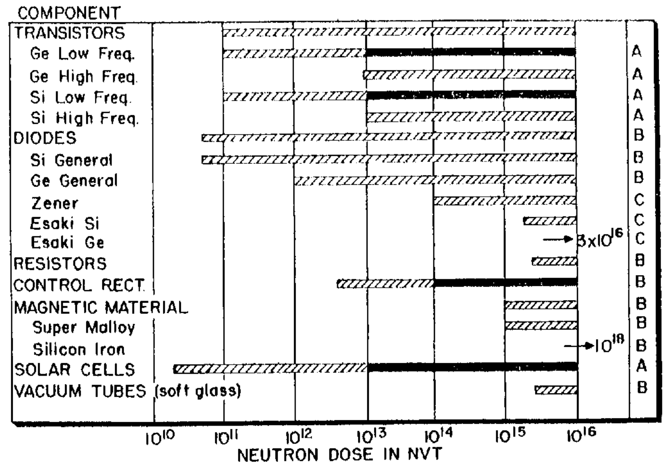


Fig. 4: Solid lines indicate neutron permanent damage levels.

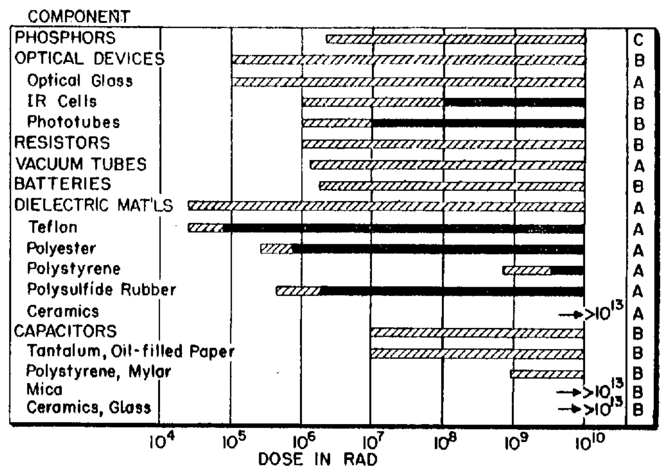


Fig. 5: Ionizing radiation permanent damage for materials.

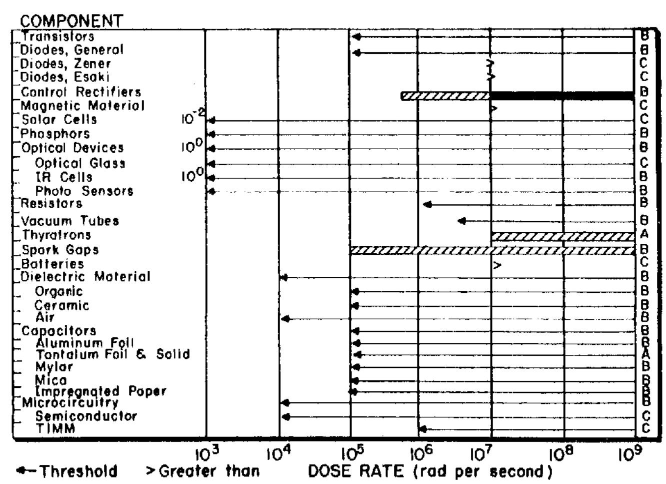


Fig. 6: Shown are levels causing transient radiation effects.

REFERENCE PAGES

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SOMETHING NEW HAS BEEN ADDED

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Nuclear Packaging *(Continued)*

example of this type of work is given by Blair, et al.,[3] where a transistor amplifier circuit was constructed which would withstand a total radiation dose of 10^{16} nvt. However, in many instances there are upper limits on what range of radiation dose can be tolerated by certain types of equipment. For example, 10^{16} nvt is probably an upper limit for present day transistor configurations. Other components, such as infrared detectors and organic dielectric materials also have limited usefulness, as shown in Figs. 4 through 6.

One method of overcoming component limitations is to investigate new design concepts. For example, in solid state components the tunnel diode appears to have a higher intrinsic radiation damage level than normal transistors. It should also be noted that vacuum tube components, particularly ceramic vacuum tubes, have a very high permanent damage capability. They are also more resistant to transient radiation effects than are semiconductor devices, except perhaps the tunnel diode.

Fig. 7: Plot of E_{CGX} versus dose rate of a 2D21 Thyratron tube.

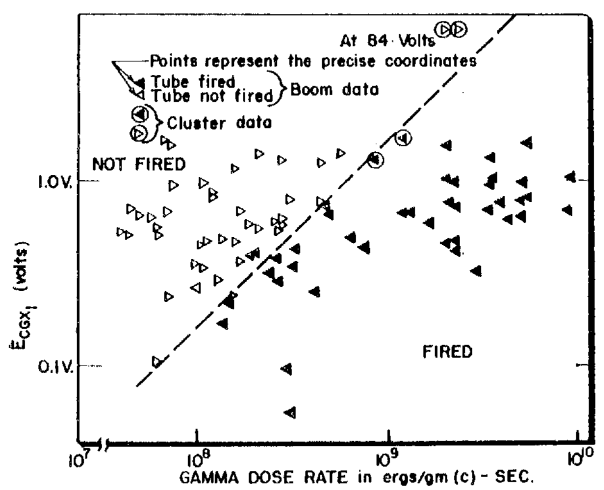
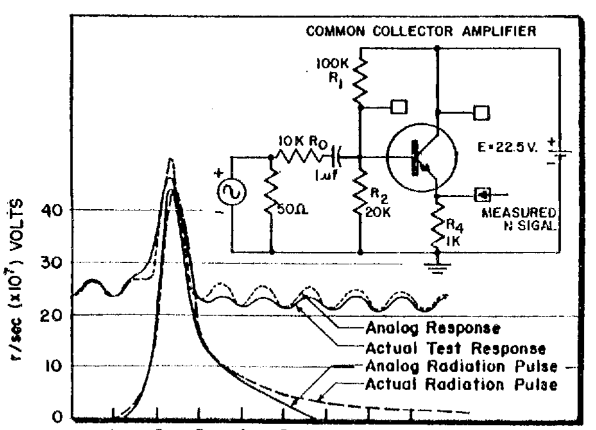


Fig. 8: Simulated and actual response of amplifier circuit.



People engaged in radiation effects testing work have discovered many rules of thumb that can be used to reduce the radiation susceptibility of their test instrumentation. These rules are also valid for general circuit design application. The rules apply to the particular type of environment considered and they must not be applied indiscriminately to all environments.

For a transient radiation effects environment, where very high radiation rates are encountered, it is quite common to cover all electronic leads that are exposed to air with some suitable potting compound, such as wax or silastic. This reduces the effects of air ionization. If the potting compound has a substantial thickness, the effect of Compton scattering from the electronic component material is also reduced. This reduction in Compton scattering is accomplished by the fact that Compton electrons are scattered into the components from the potting compound, as well as out of the component. In a reactor environment where the radiation rates are much lower, this technique may not be desirable due to the permanent radiation damage that could occur in the potting material itself if an organic potting material is used.

Another example which is of interest for a transient radiation environment is the construction of circuits which are tolerant to noise. The transient radiation pulse in electronic circuits can be quite similar to a noise pulse induced by an ordinary electrical transient. If a circuit is tolerant to noise pulses, the probability of malfunction due to transient radiation-induced pulses will be low. It is also desirable in many instances to keep impedances low. For example, when a vacuum tube is exposed to a radiation pulse, it appears as if a current generator having a strength $i_g = a\gamma$ is placed in series with the grid of the vacuum tube. (Where γ is the radiation rate in r/sec and a is 4×10^{-13} amp-sec/r for a 7586 RCA nuvistor.) When the grid impedance is low, the voltage output of the tube will be small. If the input impedance is high, the radiation-induced output will also be high. It is also possible to increase the radiation rate at which thyratrons will trigger by biasing the thyratron grid more negatively. The grid bias characteristics for the 2D21 are shown in Fig. 7 as obtained by IBM,[4] where E_{CGX} is the excess grid bias above the voltage at which the tube normally fires.

Another aspect of radiation damage, particularly permanent damage to components, is that if the reduction in the performance of the component is known, circuit feedback can be used to reduce the effect of degradation of the component. This is a common technique. It has been used by Boeing designers to decrease the effect of the transistor gain reduction in transistorized circuits. The reduction in the gain of transistors due to neutron radiation is well known.[5, 6] It can be predicted easily within a factor of two for most transistor types. Once this degradation is known, it is very easy to apply standard design techniques and obtain transistor circuits which will have a usable output over a known radiation tolerant range.

Advanced Circuit Design Concepts

A new design concept is being developed at Boeing[6] which can be used to predict the effects of a transient radiation environment on equipment. The essential feature of this technique is the use of an analog computer. The computer simulates both the radiation environment and the response of the electronic components to the radiation environment. The response of simple transistor circuits to a critical assembly pulsed environment has been successfully predicted (Fig. 8). As this technique is developed and expanded to include other components and other types of environments, it should prove valuable in predicting the response of circuits to any arbitrary radiation-pulsed environment.

Summary

It has been shown that the methods of designing and packaging electronic equipment can be used to substantially reduce the effects of nuclear radiation. These techniques are in use or have been developed, and newer concepts should be available soon. Using these techniques, it will be possible to design electronic equipment which will function in radiation environments higher than normal electronic circuit design techniques would allow. The design engineer should be mindful of this problem. When he recognizes the possibility of a radiation environmental problem he should consult either the literature or persons competent in this field for aid. In so doing, he should be able to solve his electronic design problems.

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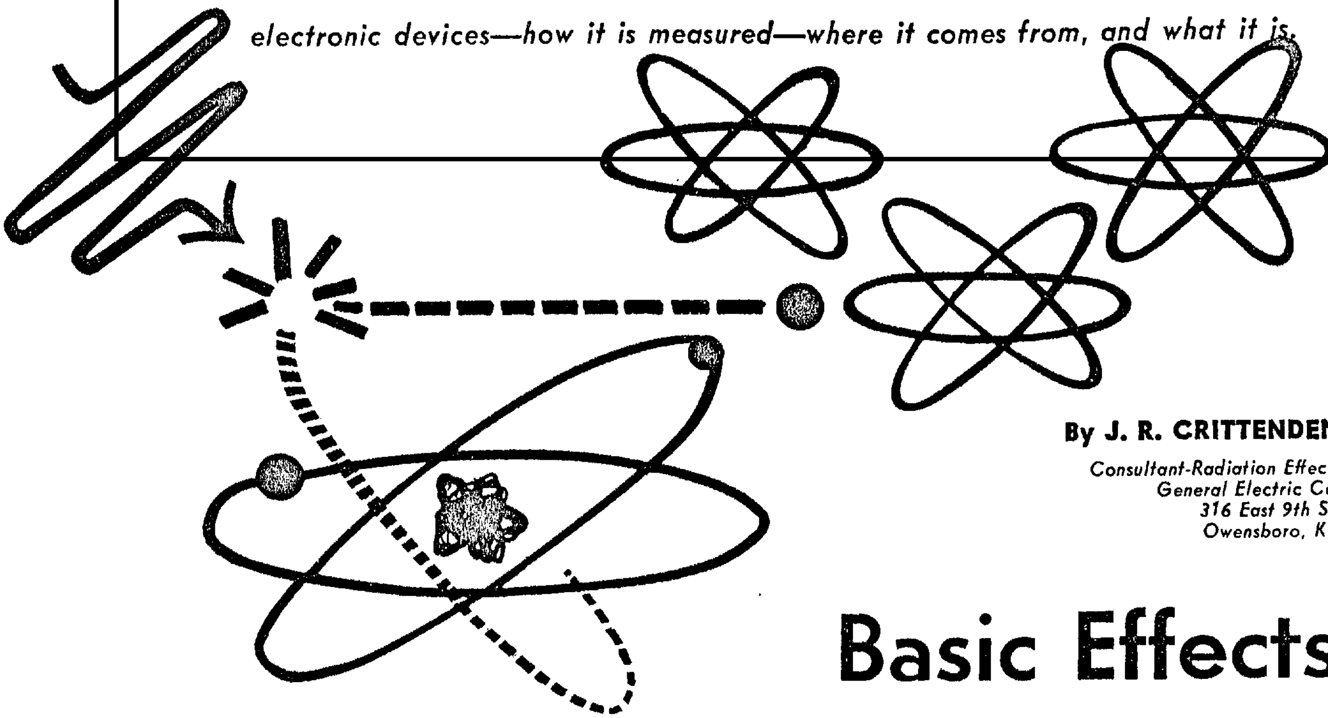
6. "Predictions of Transient Nuclear Radiation Effects in Electronic Circuits-Summary," Report on Air Force Contract AF33(616)-7804, ARPA Order No. 179-61, Boeing Doc. D2-9878.

More and more requirements for greater equipment reliability are being made. One of these is for more nuclear radiation tolerant equipment. To achieve this the engineer needs to know how radiation affects materials and electronic devices—how it is measured—where it comes from, and what it is.



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Basic Effects of Nuclear Radiation

AFTER learning how to build electronic equipment to survive drop tests, shake tests, temperature extremes, and mishandling (to mention only a few contemporary environmental requirements), the designer of electronic equipment is being given a new problem. The increasing efforts to use nuclear energy as a power source and to explore space are combining to make the effects of nuclear radiation an important design consideration for electronic equipments. To meet the challenge to build reliable, radiation tolerant electronic equipment, the designer needs to know how radiation affects materials and electronic devices, how it is measured, where it comes from, and what it is. Let's consider this last question first.

Nuclear radiation is a flow of particles or electromagnetic waves, or both, which originated in an event that involved an atom's nucleus. When these particles flow into or through a material of interest, some or all of them interact with the atomic structure. Radiation effects are the results of these interactions.

Nuclear radiation may consist of charged particles, a neutral particle, electromagnetic waves, or any combination of these. Charged particles have both mass and an electrical charge. They range from the beta ray, an electron emitted with high energy from the excited nucleus of an atom, to fission fragments which are the heavier nuclei produced in the fission of uranium. Protons (hydrogen nuclei) and alpha particles (helium nuclei) are two of the more frequently discussed examples of charged particles. To the designer of electronic equipment, there is only one neutral particle of interest, the neutron, which has mass but does not have an electric charge. Electromagnetic waves which emanate from a nucleus (as opposed to those which are produced by an excited electron falling to an orbit of lower energy) are called gamma rays and are similar to x-rays. They have no mass and are unaffected by either magnetic or electric fields.

Penetrability

Because charged particles carry one or more unit electrical charges, they are affected by both electrical and magnetic fields. The fields which exist about each atomic nucleus repel all but the most energetic charged particles. Even though a collision, in the physical sense, between a charged particle and a nucleus does not usually occur, the interaction between the fields of the charged particle and the nucleus takes energy from the motion of the charged particle. Charged particles also give up energy to electrons as they pass near them. As a result of the frequent interactions, charged particles follow a tortuous path and do not have long ranges in most materials. In other words, they do not penetrate deeply and give up their energy near the surface of most materials. Charged particles, however, may produce serious effects over short distances.

Neutrons and gamma rays, which are unaffected by the fields that surround nuclei, have very long ranges and do penetrate deeply, even in dense materials. Because they are difficult to stop, or absorb in

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rays, but do not have the same range and do not, then, tend to escape the system.

The protons of the lower Van Allen belt have relatively high energy and penetrate the entire system. The proton paths are easily observed by the ionization they produce. When a proton from the lower Van Allen belt interacts with a nucleus, it may transfer several million electron-volts. The nucleus with which the proton collides is displaced and usually has enough energy to displace many other nuclei. One proton interaction may bring about a series of displacements and create a small zone of intense ionization. The energy introduced into the system is transferred throughout the system as it diffuses to thermal equilibrium. (Radiation does add energy to a system and can be detected by observing the temperature rise.) Thus, one high energy proton may produce a zone of intense ionization and displacement, and a general increase in ionization in the system.

If the proton interaction occurred in an inorganic insulator (an ionic compound), the change in conductivity it produces is probably insignificant and there are few permanent effects. If it interacted in an organic material, the change in conductivity is probably not detectable, but permanent effects are produced. In a semiconductor, the proton interaction may produce noticeable changes which are permanent because displacements appear in the structure. The sum of these individual events is the effect of nuclear radiation.

There are many other types of radiation effects, such as photo-voltaic currents or F-center generation, which are beyond the scope of this discussion. These effects are present in all irradiations, and in many cases complicate the design of radiation tolerant electronic equipment. Fortunately, in designing radiation tolerant electronic equipment, most of the other effects may be neglected.

In most practical instances, the radiation intensity is relatively low, which means transient effects are negligible; or when the intensity is high, the time duration of exposure is short; and permanent effects may be disregarded. Few applications combine both high intensity and long exposure.

Measurements

To design reliable, radiation tolerant electronic equipment, it is vitally necessary to define the content, spectrum and magnitude of the radiation field. The penalties for over-design may be quite costly. Useful materials and components may be abritrarily eliminated. The penalty is, however, just as costly when weak materials and devices are selected. Because there is a considerable amount of radiation effects information available, definition of the anticipated environment enables the designer to choose electronic components intelligently.

Nuclear radiation is detected and measured through one of three basic processes. Ionizing radiation produces conductivity changes. These may be observed with an electric circuit. Displacing radiation transfers energy to other particles which may be observed. Transmuting radiation is measured by observing the particles and energy released, or by chemical analysis.

The geiger counter is probably the most familiar instrument for detecting and measuring nuclear radiation. It is a special form of an ionization chamber, which is a container filled with a gas, having electrical connections geometrically arranged so that the electrons and ions, generated by the passage of ionizing radiation, may be converted into electric current. The output signal, then, is directly proportional to the intensity (dose rate) of the field.

The amount or time integral (total dose) of ionizing radiation may be obtained by integrating the out-

DEFINITIONS

beta rays	high energy electrons ejected from a nucleus
protons	hydrogen nuclei
alpha particles	helium nuclei
gamma rays (photons)	similar to x-rays, electromagnetic waves (packets of gamma rays which behave as particles)
neutrons	neutral particle with about the same mass as protons
Roentgen	a quantity of ionizing radiation which will produce 2.083×10^9 ion pairs per cubic centimeter of STP air or deposit 83.8 ergs per gram of STP air.
Roentgen per hour	the intensity of a field of ionizing radiation which will deliver one Roentgen per hour
Rep	Roentgen equivalent physical (93 ergs per gram of tissue equivalent)
Rem	Roentgen equivalent mammal (that quantity of ionizing radiation which will produce biological damage equivalent to one Roentgen of X-rays).
Rad	a unit of absorbed energy (100 ergs per gram)
ergs/gram (carbon)	the preferred measurement of absorbed dose (a standard ionization chamber is used which is made of carbon and carbon dioxide).
nv	neutrons of energy E crossing a sphere of unit cross-sectional area per second, neutron flux (neutrons per square centimeter per second)
nvt	the time integral of neutron flux (neutrons per square centimeter)
flux	the flow of radiation
dose	absorbed energy
dose rate	the rate of radiation or intensity
Mev	million electron-volts
barn	10^{-24} centimeters^2 (a measure of the probability that a nuclear interaction will occur)
cosmic rays	very high energy particles which permeate space
Van Allen belts	trapped particles found in two zones about the earth's geomagnetic axis—the lower maximum consists of protons and electrons, the upper maximum is apparently only electrons

put of an ionization chamber, or it may be measured directly by analyzing the chemical change produced in certain compounds. In some materials (glass is a good example), the total dose may be determined by measuring the increase in optical density, which is directly related to the number of ionizing events.

Neutrons are detected and measured with a modified ionization chamber. Easily captured neutrons are detected by observing the energetic charged particles released in a selected transmutation. Faster neutrons are observed by transferring some of their energy to an easily detected charged particle. The output signal is proportional to the magnitude of the neutron flux.

The total number of neutrons (integrated flux) is determined by analyzing the interactions in selected materials. The energy ranges over which many transmutations occur are well defined. By selecting appropriate transmutations, it is possible to measure the magnitude and to define the spectral content of a neutron flux.

The spectral distribution and content of an ionizing radiation field is defined by filtering and noting the magnitude of the interaction. The spectrum of ionizing radiation is defined by its ability to penetrate. Soft or low energy radiation can be stopped (filtered) by a thin layer of material. Hard radiation requires thicker layers. Heavy charged particles create more ionization in a short path than electrons and gamma rays. Thus, the amplitude of the output signal of an ionization chamber device and the filter thickness describe a field of ionizing radiation.

In all measurements of radiation, though, the field is described indirectly. The flux is determined by what happened in a selected, calibrated situation. The radiation field itself is only inferred from the measurement. For this reason, considerable care must be used in interpreting radiation field measurements.

Conclusion

The design of reliable, radiation resistant electronic equipment is much the same as designing equipment to withstand drop tests, shake tests, and mishandling. Nuclear radiation acts throughout a system on all its parts, and its effects are complex. Most of the macroscopic effects may be analyzed in terms of the fundamental effects. As a result, nearly all nuclear radiation effects can be predicted.

The designer of reliable, radiation tolerant electronic equipment needs to know what nuclear radiation is, how it is measured, and what its effects are. With this information and a clear definition of the requirements, the challenge can be met.

It is the author's privilege to acknowledge the assistance and valuable aid rendered by J. D. Jordan, S. E. McCallum, A. D. Sanders, E. D. Greene, and many others. Their efforts and interest are greatly appreciated.

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This is the second article in our planned series about pulsed nuclear radiation effects. Here we learn how pulsed radiation affects insulating materials, metals, semiconductor materials, gases, and other electronic materials as an aid in designing radiation-proof equipment.

Effects of Nuclear Radiation on Electronic Materials

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THE study of nuclear radiation effects on materials is now an important subject. There are two general types of environments. In the first, the interest is in the long term, more-or-less permanent, effects of high energy irradiation on materials, usually in the neutron and gamma ray flux of a reactor. In the second, the interest is in the transient behavior of a material or electrical component in the high intensity time-dependent flux of a nuclear weapon.

Interest in transient radiation effects comes from the need for information on the behavior of military systems in this type of environment. It consists primarily of a short, prompt, intense pulse of gamma rays and a slower, broader pulse of fast neutrons. It would be an unnecessarily severe restriction to have to rely solely on nuclear weapons tests to provide the environment for experiments. We can simulate, in part, this environment in the lab. by the use of pulsed reactors. From the standpoint of permanent radiation damage, the pulsed reactor is also useful because it provides high doses without the thermal effects and the thermal neutron environment of a steady state reactor.

For transient radiation effects, the prompt gamma ray pulse is reasonably simulated with a linear electron accelerator, in which the electron beam is converted to gamma rays by the process of bremsstrahlung in a high-Z target. For this purpose, accelerators have been designed which stress a high current electron beam in order to obtain high intensity bursts of gamma rays.

Radiation Effects in General

There are several effects of nuclear radiation that are common to all materials. These will be discussed first. Then, effects characteristic of particular materials, insulators, semiconductors, and metals will be discussed in more detail.

Neutrons and gamma rays, that make up the nuclear radiation flux, in their interaction with matter behave in distinctly different ways. The neutron, since it is an uncharged particle, will not interact with the electron shells of atoms. Instead, a fast neutron (defined as one with a kinetic energy in the range of one million electron volts) will lose energy in collisions with the nuclei of the atom. In these collisions, sufficient energy is usually imparted to the struck atom to dislodge it from its proper place in the lattice of a solid. This struck atom, termed the primary "knock-on," may, in turn, have enough kinetic energy to dislodge secondary atoms which, in turn, will cause further displacements, so that a cascade process results. Calculations indicate,[1] for example, that the mean number of displaced atoms per primary knock-on in carbon, due to reactor irradiation, is 900.

In contrast, for the case of gamma rays, interaction with the atomic electrons rather than the production of displaced atoms is the important effect. This interaction takes the form of excitation and ionization of the atoms. And, as might be expected, chemical reactions may be induced in the material under irradiation. With these characteristically different effects in mind, atomic displacements in the case of neutrons, and atomic ionization in the case of gamma rays, we may discuss in more detail how they show-up in insulators, semiconductors and metals.

Insulators

Insulating materials may be subdivided into two categories: organic and inorganic. In general, radiation effects in the former class of materials are hard to describe precisely because of their dependence, for

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example, on environmental conditions and on the rate at which the radiation is delivered. In the case of organic insulators, studies indicate that the most important effects from exposure to radiation are: (1) cross linking; (2) chain cleavage; and (3) ionization.[2] An effect that confirms that chemical reactions are occurring is that gas is evolved during irradiation. In the case of Teflon and Fluorothene, fluorine and chlorine, respectively, are evolved. This may cause corrosive action in surrounding materials.[3] For Teflon, additional work[4] tends to show that there is also an environmental factor present where the breaking strength of this material is concerned. A comparison of effects produced by gamma irradiation, in air and in vacuo, shows that the reduction of breaking strength is less in the latter case.

Pigg, Bopp, Sisman, and Robinson have studied the breakdown of insulators in a reactor flux. The time-integrated neutron flux at which breakdown occurs in several organic insulators, as determined by them, is given in Table 1.[5]

Generally speaking, inorganic insulators are less susceptible to the effects of high energy irradiation. The reason being that excitation and ionization in this class of materials, unlike the organic materials, does not induce chemical reactions. Instead, the effects that occur are due to displaced atoms, which are produced by the neutron component. The effect of the gamma ray flux in this case is very small. In addition, the environmental factor is not likely to be important. For crystalline insulators such as Al_2O_3, irradiation causes an expansion of the crystal lattice, which is manifested as a decrease in density. For integrated fluxes in the range of 10^{19} to 10^{20} fast neutrons/cm^2, the observed changes were of the order of 1 to 6%.[6] In the case of materials like porcelain, alumina, and steatite, exposure to a nuclear radiation environment results, in general, in a decrease in their sensitivity and dielectric strength.[7] Amorphous inorganic materials like glass also degrade in a high energy environment, with boron glass being the most susceptible to damage.

A few words should be said about the effects on insulators in a transient radiation environment. Where these materials are used in components and circuits, the most important effect, at distances where permanent damage is negligible, may be a transient leakage conductivity induced by the gamma flux. In high impedance circuitry, pulses resulting from this effect can be disruptive. Experiments show that this becomes important at gamma fluxes of the order of 10^6 roentgens per second.

Semiconductors

Because of the widespread use of semiconductor materials, the problem of their behavior in a nuclear radiation environment is important. A great deal of effort has been spent in finding the nature of the radiation effects. It is interesting that the information obtained has aided the solid state physicist in his search for an understanding of matter. Also, it helps the engineer to select components that will function best in any type of environment.

The main cause of the relative sensitivity of semiconductors to high energy radiation is the "structure-sensitive" nature of their electrical conductivity. In general, the production of lattice displacements in this class of material introduces energy levels in the forbidden energy regions of the crystal's energy level scheme. The net effect of this is to alter the distribution of electrons and holes in this level scheme, and so alter the measured equilibrium conductivity of a semiconductor sample. In addition to this effect of changing the equilibrium distribution of carriers, the radiation produced energy levels modify the process whereby excess carriers recombine. The minority carrier lifetime, a parameter of importance in the operation of semiconductor devices, which is determined by the process, is accordingly affected. For example, in a sample of 50 ohm-centimeter n-type germanium, the minority carrier lifetime was observed to decrease by almost two orders of magnitude as a result of exposure to 3×10^{13} neutrons/cm^2 of fast neutrons.[8] In a similar experiment with gamma rays from radioactive Co^{60}, an exposure to 2×10^{18} photons/cm^2 produced a similar decrease in lifetime in another sample of n-type germanium.

The minority carrier lifetime is the semiconductor parameter most sensitive to radiation. Under prolonged exposure to high energy radiation, more profound changes occur in semiconductor properties. N-type germanium will finally be converted to p-type, while initially p-type material becomes more p-type.[9] In the case of silicon, either n- or p-type is converted to intrinsic.[10]

Table 1

Insulator	Breakdown Exposure Dosage (neutrons/cm^2)
Polystyrene	10^{20}
Polyethylene	10^{19}
Silastic 80	10^{19}
Sil-X	9×10^{18}
Teflon	5×10^{18}
Silicone Rubber	4×10^{18}
Neoprene	3×10^{18}
Formvar	2×10^{18}
Polyvinyl Chloride	1.9×10^{18}
Rubber	1.3×10^{18}
Kel F	10^{18}
Supronant A-10	10^{17}
Supronant B-10	5×10^{16}

A somewhat different behavior can be seen in semiconductors under transient high energy irradiation conditions, in contrast to the case of steady-state irradiation. It is due to the effect of ionization rather than to the production of atomic displacements, and is peculiar to semiconductors. Briefly, a high intensity pulse of irradiation incident upon a semiconductor will create free electrons and holes, just as would a pulse of light. Since the conductivity of a semiconductor is proportional to the densities of these carriers, a transient change of conductivity will result that may be detected, if means are provided for this type of measurement, during and after the radiation pulse. Studies show that the characteristic time of decay of excess conductivity, produced in this way, is of the same order of magnitude as the minority carrier lifetime. This type of transient effect is of primary importance in a pulsed high energy environment. It is distinct from those persistent effects discussed previously that are the result of prolonged steady-state irradiation.

Metals

In contrast to the case of insulators and semiconductors, ionization effects are negligible in metals. The effect of irradiation is due entirely to atomic displacements and, therefore, the fast neutron component of a reactor irradiation will be the one of importance. As explained under General Effects, the fast neutron will undergo an elastic collision with a lattice atom, knocking the atom out of its lattice position and giving it considerable kinetic energy in the process. Additional displacements are produced; and, to the extent that the particular physical property of a metal is determined by defects in its lattice, the property will undergo a change.

Fast neutron irradiation increases the yield strength of metals in general. Tensile strength is also increased. The extent of the effect, however, depends upon temperature, and radiation damage may be reduced or removed by proper annealing. Two examples of irradiation effects in metals are as follows: An increase in the critical shear stress from 0.241 to 2.00 kg/mm^2 occurred in a copper single crystal for a fast neutron exposure of 2×10^{18} neutrons/cm^2.[10] SAE 1019 steel was bombarded with 18.6 Mev deuterons and a change in the brittle property was observed through a change in the transition temperature from $-1°C$ to $18°C$.[11]

Gases

Only a very small amount of work has been reported on the effects of radiation on gases. Some experiments on the polymerization of acetylene and ethylene gases have been done at Yale University. There is also some work that indicates that carbon dioxide is decomposed by ionizing radiations. Such decomposition may be expected in gaseous compounds at some level of radiation. As for the elemental gases such as oxygen, nitrogen, etc., however, there is little that can happen aside from ionization. From first considerations, one would expect appreciable transmutations of the elements only at very high thermal neutron doses.

From the standpoint of transient radiation effects, the ionization of gases can be important. In particular, the ionization of the air around components and circuits leads to leakage currents of significant values, in high impedance circuitry, at gamma fluxes of the order of 10^6 roentgens/sec.

Miscellaneous Materials

Aside from the effects of radiation on the performance of insulators, conductors, or semiconductors, there are a few materials used in electronics because of other properties such as magnetic permeability, dielectric polarizability, and piezoelectricity. In general, the transient radiation effects in these properties are negligible, but reactor radiations usually result in some measurable degree of permanent damage.

Among the ferromagnetic materials, ferrites have shown no permanent effects, while the metal alloys suffer considerable damage.[11] Supermalloy seems to be the m[illegible] max the least affected. The latter alloys show a 50% increase in coercive force and a small decrease in initial permeability. Some Mo-Permalloy materials show a decrease as much as 80% in initial permeability and a change in the shape of hysteresis loop.

There have been a few experiments with ferroelectric materials, which are unique for their high dielectric polarizability. Tetragonal crystals of barium titanate are converted to the cubic form at 1.8×10^{20} fast neutrons/cm^2 because of atomic displacements.[12] This greatly reduces the dielectric polarizability. Some work with ceramic disk capacitors, using dielectrics of barium titanate and lead titanate zirconate compounds, show that gamma radiations may reduce the capacitance by as much as 10%, along with a decrease in the dissipation.[13]

Quartz crystals were tested for radiation effects in a number of ways. There is little evidence of an appreciable transient radiation effect in the work done with pulsed radiation sources. Permanent effects have been observed with steady state reactor radiations.[14] This effect consists of a large change in the resonant frequency of the crystal. No such change was found in tests with a pulsed reactor. This indicates that the large thermal neutron flux of the steady state reactor is largely responsible for these effects. However, large doses of x-radiation cause permanent changes also. Certain cuts are more susceptible than others. Bottom and Nowicki[15] found that AT, AC, and DT plates, irradiated to saturation with x-rays were little affected. BT and CT units on the other hand were appreciably affected.

Some capacitor dielectrics experience physical changes which may result in rupture or destruction of the capacitor. Liquid dielectrics, for instance, may show some solidification or a decomposition into acids and gases. Electrolytic capacitors are particularly susceptible, showing both a transient breakdown to pulsed radiation and permanent damage due to physical changes in the dielectric.

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Requirements for radiation hardening are reviewed in relation to military requirements. Problems connected with the evaluation of parts during and after irradiation are discussed. A review of the state of the art for nuclear resistance parts is covered.

NUCLEAR BLAST EFFECTS ON COMPONENTS & EQUIPMENT

No. 4 in EI's Series on Nuclear Radiation

MILITARY ELECTRONICS EQUIPMENTS must operate reliably, accurately, and dependably in nuclear environments. The design and development of electronic equipment, the performance of which under field use will not be affected deleteriously by nuclear radiation, must be based upon the results of thorough investigations of the vulnerability and reliability of the electron devices used in equipment, when subjected to nuclear radiation.

A program for the improvement of electronic components for the nuclear environment is now being pursued by the Signal Corps. It was found that statistical data for use in equipment applications were severely lacking in many areas. In fact, experimental data on the behavior of electron tubes in complete circuits were also found to be very limited. Acquisition of these data in depth is now being planned.

Effects of Radiation on Parts

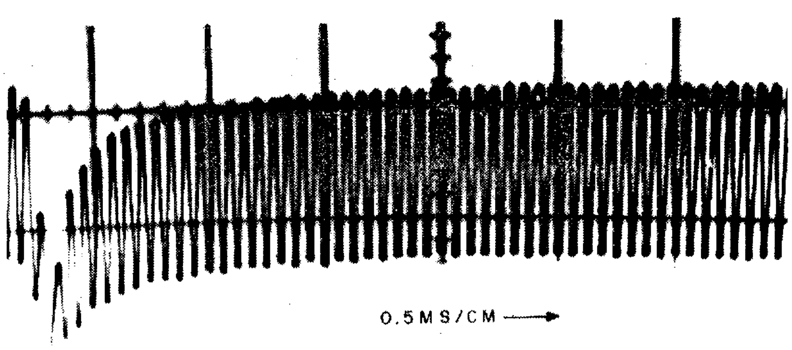
Let us now examine each of the classes of electronic piece parts, determine the state of the art and the areas which need further investigation.

Electron Tubes

In general, electron tubes exhibit radiation tolerances superior to those of other piece parts. Information on the behavior of tubes in a steady-state radiation environment is abundant. Effects such as discoloration of glass, fractures of glass, and failure of glass-to-metal seals are major factors in tube malfunctions in a steady-state radiation environment. Investigations have shown that soft glasses and high-temperature hard glasses, such as alumina-silicate glasses free of boron, are more radiation resistant than hard glasses[1] containing boron (Nonex and Pyrex). The use of metal-ceramic seals and the elimination of glasses containing boron have shown the possibility of raising the nuclear radiation tolerance levels up to 10^{17}-10^{18} n/cm^2.

Part of this information was gained during the Aircraft Nuclear Propulsion (ANP) program. Certain types of electron tubes, after exposure to a steady-state nuclear reactor environment, consistently had fractures in the glass or gas leaks after long-term irradiation. Correlation between these effects and the different types of tubes was not initially apparent to the groups performing these ex-

Fig. 1: Typical transient response of electron tube during 60 microsec. radiation pulse.



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periments. However, to those familiar with electron tube design and fabrication, it was quite evident that the glass fractures and gassing were occurring in certain types of glass envelopes. This failure could be attributed to the type of glass rather than the type of tube. Hard glasses containing boron were causing the glass fractures and gassing. Neutron interaction with atomic boron caused glass fractures. Initially, only small leaks at the metal-to-glass interfaces occurred, which resulted in leakage into the tube. However, as the damage became more severe, failure of the glass ensued. A similar method of analysis, it is believed, will lead to the final solution of the pulsed nuclear radiation damage problem. However, each of these investigations requires much time, numerous manhours, and the availability of proper exposure facilities.

In contrast to the permanent damage observed in electron tubes at steady-state reactors, only transient changes have been recorded during pulse-type exposures. A typical transient perturbation in an electron tube exposed in a pulse environment is shown in Fig. 1. The trace represents the transient change in the ac gain.

The information on pulse radiation effects on tubes has been limited to a few types and for a very small sample size of each type. Statistical information is

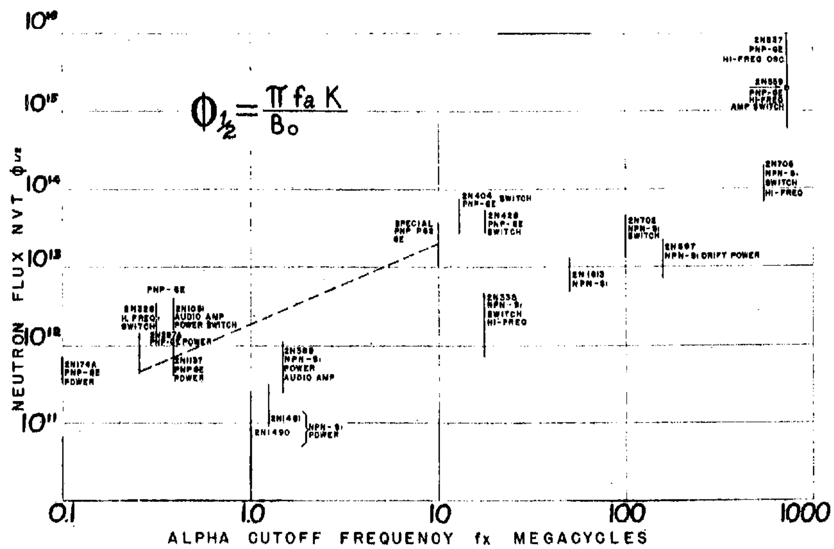


Fig. 2 (above): Shown is the radiation dosage at which a pertinent parameter of a solid state device will fall to one half value.

Fig. 4 (below): Graphs show the estimated effects of nuclear radiation on various resistors.

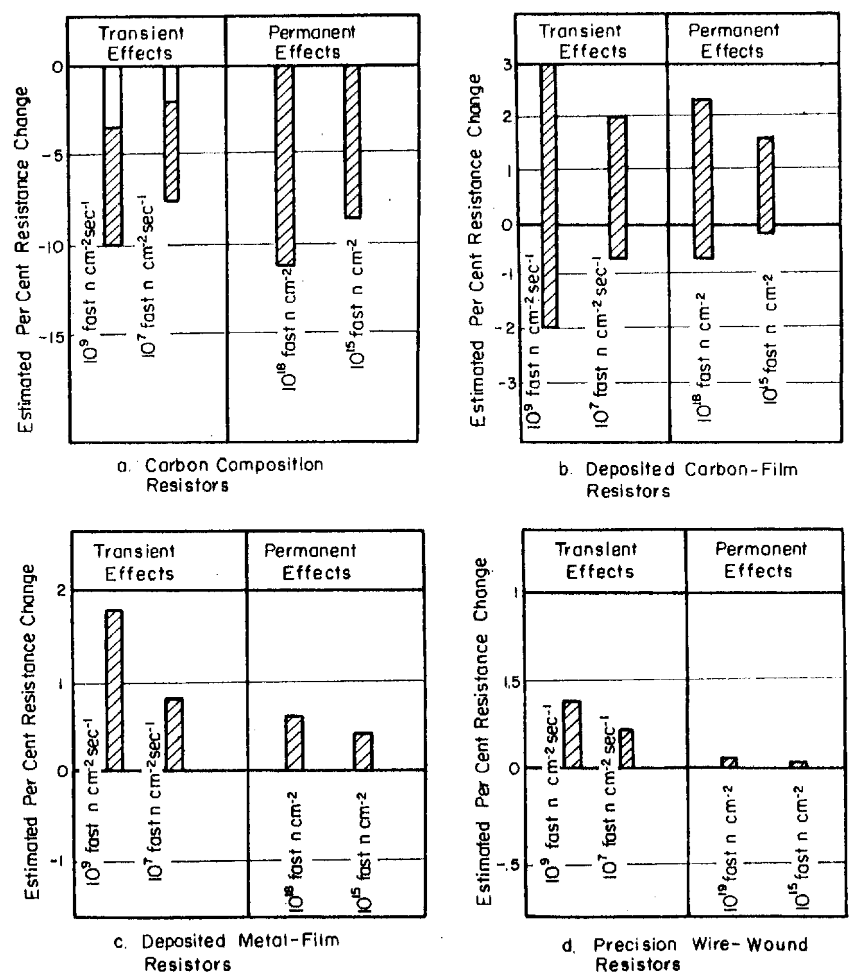
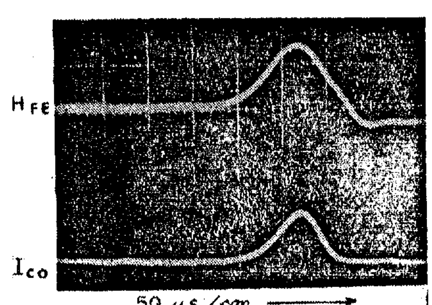


Fig. 3: Photo of typical changes in transistor parameters during radiation pulse.



lacking on many types of tubes, including microwave devices of all types, power tubes, ferrite devices, etc. Programs have been initiated by the USASRDL to investigate the magnitude of the problems associated with these special groups of devices. Specifically, studies are being conducted on the effects of nuclear radiation on a voltage-tunable magnetron.[2] This study is directed at one specific device. Later other types, which are representative of this category of devices, will be evaluated in radiation environments, and efforts for improvement started. A program is also underway to find the effects of pulse nuclear radiation on a ferrite duplexer.[3]

Several programs are also in progress to find the basic mechanisms which produce transient radiation effects in tubes. Before radiation-resistant devices are developed, it will be necessary to fully understand the basic interaction between nuclear radiation and the electron tube materials, and electron tube operation. A program is now underway to ascertain the quantity and type of gases evolved in tubes during a pulse nuclear radiation.[4] Another comprehensive program has been started to investigate such phenomena as radiation-induced conductivity in tube insulating material, secondary electron emission from tube material, and correlation studies between effects, radiation rate, and spectrum.[5]

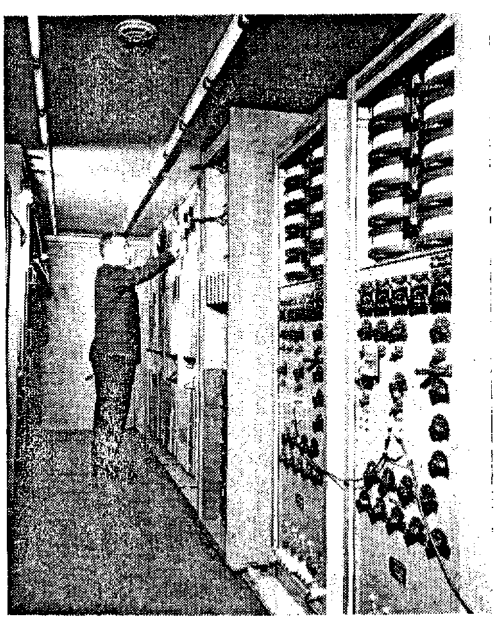


Fig. 5: Interior of a radiation effects mobile laboratory used by Signal Corps at Ft. Monmouth.

Semiconductor Devices

Permanent radiation damage in semiconductors is blamed on defects caused by fast neutron interaction in the crystalline lattice structure. Impurity atoms are formed, vacancies and interstitials thus created change the electronic equilibrium in transistor operation. The degree of permanent change is proportional to the total integrated fast neutron dose, and varies with materials and construction. Transient effects in transistor operation are caused by the interaction of gamma radiation with orbital electrons, and ionization resulting from atoms which are displaced by fast neutrons. Because of the large mobility of these electron-hole pairs, effects exist only as long as the source of ionization or radiation is present. Thus, a transistor exposed to a pulse of mixed radiation will exhibit both a transient and permanent change after exposure. The permanent change may anneal-out in seconds, minutes, or days.

In some complex military electronic systems a change in device parameter, lasting in the order of seconds, cannot be tolerated. Also, when the transient and permanent changes in transistors are coupled with the transient changes in resistors, capacitors, insulators, etc., serious difficulties can arise.

In general, it can be stated that h-f germanium devices are many time more superior in radiation resistance than low-frequency or power silicon devices. A chart depicting this range in devices is shown in Fig. 2. This chart represents the radiation dosage at which a pertinent parameter will fall to one-half its original value. As can be seen, a spread exists through 3-4 orders of magnitude.

Some typical results of transient effects in semiconductor devices are shown in Fig. 3. The top trace is the change in forward current transfer ratio H_{FE}, while the lower trace is the transient change in leakage current I_{CO}. Note the permanent change in H_{FE}. This particular device is a h-f germanium switching type. The results are part of the data obtained during a recent Signal Corps experiment at a pulsed reactor, where about 500 solid state devices (20 types) were exposed to the pulsed nuclear environment. This experiment was done to ascertain the radiation damage vulnerability of some of the most recently developed solid state devices. In addition, the relatively large number of each type of device will provide a basis for statistical analysis. With this type of information, it will be possible to plot curves showing data on variations and confidence limits of each type of device. The equipment designer can then use this information for the selection of components which must operate in a radiation environment and compensate for the perturbation.

Additional theoretical studies are being conducted to define the basic mechanisms which produce transient effects in transistor operation.[6] Early device improvement studies have resulted in prototype models which have radiation resistance to orders of magnitude higher than the same devices of previous design.[7]

More research is needed on some of the new materials being used in semiconductor construction. Concomitant with the new materials, newly developed devices must be evaluated in a pulse radiation environment. At present, much of the available information is unreliable due to errors attributed to the manner of data acquisition. Many times the spread of data is so wide that the data cannot be used by the equipment designers. Experiments to be conducted in the future should be designed using statistical methods, proper sample sizes, techniques, etc., including dosimetry.

Resistors

Present information on the effects of steady-state nuclear radiation on resistors shows that the ranking of tolerance is as follows: wire wound, metal film, carbon film, and carbon composition. The threshold for damage for carbon composition is 10^{13} n/cm^2, while wire wound resistors can withstand exposures up to 10^{19} n/cm^2. Early data on the effects of transient nuclear radiation on resistors showed that the major problem was due to shunt leakage paths across the resistor caused by air ionization. This has since been shown to be only one of the contributing factors. Experiments are being performed to learn the significance of variables such as physical size of resistor, ohmage value, applied voltage, and manufacturing processes.

A brief summary of the data which exist on resistors in a radiation environment is shown in Fig. 4.[8] When using this chart, it must be realized that the definition of failure in these cases is somewhat arbitrary. Many conditions and factors influence the judgment of whether a resistor has exceeded its critical parameter tolerance. The chart does not represent any single experiment or manufacturer's type of resistor.

More research is needed to determine the significance of cable effects on resistors during experiments. During some experiments, the same effect is observed with or without the resistor at the end of the cable. Statistical data are lacking on variations in resistor effects in relation to the manufacturer. More experimental data are needed on thin film re-

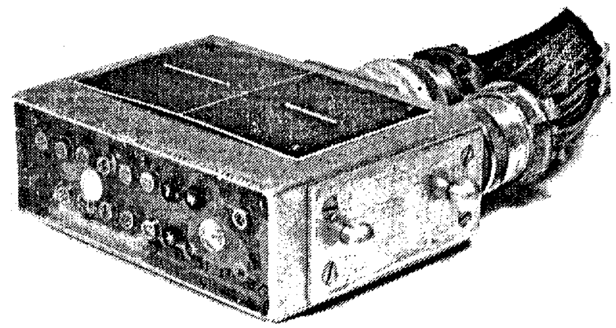


Fig. 6: Typical test head for transient radiation effects studies.

sistors. Standardization and improvement of measuring techniques are also needed.

Capacitors

A brief summary of the effects of nuclear radiation on capacitors and their tolerance is given as follows:

Ceramic Dielectric Capacitors: Ceramic capacitors exposed to a total integrated neutron dose of 1.3 x 10^{18} n/cm^2 and 2.5 x 10^{10} ergs g^{-1} (C) showed increases in capacitance of between 3.7 and 18.8% of their initial value. Upon removal from the radiation field, the capacitance generally returned to within its original tolerance value. Ceramic-type capacitors exposed to pulse nuclear radiation levels of 10^{17} fast n/cm^2.sec and 10^9 ergs g^{-1} (C) sec^{-1} showed negligible transient effects during the radiation pulse. Permanent changes varied between –3.2 and +8.7%.

Glass Dielectric Capacitors: Glass and vitreous enamel capacitors exposed to an integrated neutron dose of 2.5 x 10^{17} fast n/cm^2 and 6.1 x 10^{10} ergs g^{-1} (C) showed changes in capacitance of +2% or less, and decreases in insulation resistance of 2 to 3 orders of magnitude during irradiation. Pulse radiation experiments (Godiva reactor) on glass capacitors have shown little or no effect on their electrical characteristics.

Mica Dielectric Capacitors: Mica capacitors exposed to an integrated fast neutron dose of approximately 10^{14} n/cm^2 and 5.7 x 10^8 ergs g^{-1} (C) showed only small changes during irradiation. However, these changes remained after removal from the radiation field. Pulse nuclear radiation (Godiva reactor) has shown little effect on mica capacitors.

Paper & Oil-Impregnated Paper Dielectric Capacitors: Paper and oil-impregnated paper capacitors have shown significant changes at integrated neutron doses of about 10^{18} n/cm^2 and 2.5 x 10^{10} ergs g^{-1} (C) gamma radiation. In almost all cases, the electrical characteristics of this type capacitor were beyond tolerance levels. In general, these capacitors are more sensitive to radiation than the inorganic types by factors of from 100 to 1000.

Plastic Dielectric Capacitors: Inorganic dielectric type capacitors are superior to the plastic dielectric type by a factor of 10. The capacitance of a plastic dielectric capacitor increased about 14% after exposure to 7.2 x 10^{18} n/cm^2 and 6.1 x 10^{10} ergs g^{-1} (C) gamma units. No permanent changes were observed.

Electrolytic Capacitors: Changes in capacitance have varied between –9.7% and +25% for tantalum capacitors, and –6.0% and +65% for aluminum-type capacitors. The neutron and gamma dose ranged between 3.4 x 10^{12} n/cm^2 (5.7 x 10^8 ergs g^{-1} (C)) and 2.5 x 10^{18} n/cm^2 (4.4 x 10^{10} ergs g^{-1} (C)). Changes have been observed in tantalum capacitors in a pulse radiation environment. However, it was considered that these changes were attributable to other causes.

Quartz Crystals

Effects observed early in the program on quartz frequency control crystals were later attributed to shunt leakage paths. More recently, transient effects were observed in the CR-18, CR-52, and CR-56 military-type crystals at the Godiva II reactor and the Linac. These effects were evidenced by phase changes ranging between 10° and 90°, lasting up to at least 5000 μs. Experiments conducted at steady-state reactors indicate that aluminum-plated crystals are less susceptible to radiation damage than gold and silver-plated crystals. Damage levels vary between 10^{14} n/cm^2 to 10^{18} n/cm^2. Manufacturing processes appear to be an important factor in the degree of effect.

More research is being performed to learn the effects of short pulses of neutron and gamma radiation on quartz crystals.[10] Experimentation is needed to provide statistical information from which theories as to the mechanism of the radiation damage can be formulated.

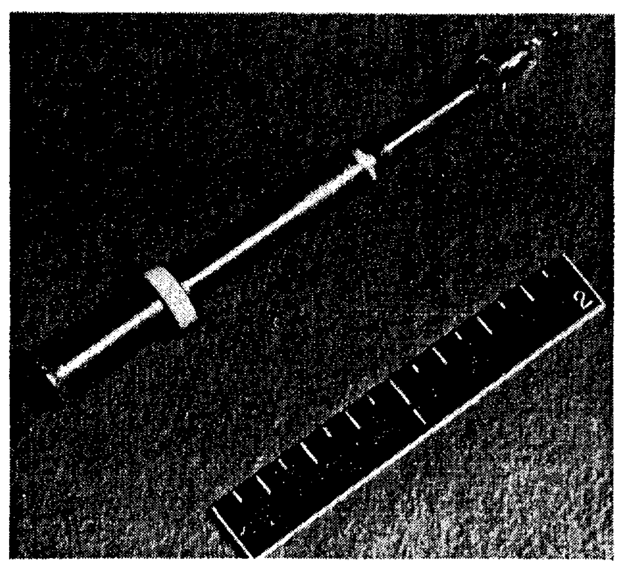
Magnetic Materials[11]

Ferrite cores exposed to a neutron dose of 1.6 x 10^{17} n/cm^2 at a steady-state reactor showed no permanent change. Experiments were conducted at the Sandia Pulse Reactor to detect changes in magnetic cores during radiation pulses. The integrated neutron dose during these exposures was about 2 x 10^{12} n/cm^2 $E > 2.5$ Mev. Mg-Mn ferrite (wide temperature range) memory cores, Cr-Mn-Ni-Zn ferrite and 4-79 Permalloy-type switching cores showed no variations due to irradiation. Transient effects were not observed in 4-79 Mo-type Permalloy tape (logic application). However, post-test voltage measurements showed a 30% decrease. Permanent damage measurements, performed several days later, indicated the 4-79 Permalloy tape had returned to its original state. The post-test voltage decrease may have been caused by a drive current change. Mg-Mn ferrite memory devices have shown some changes during radiation pulse. Post-irradiation measurements indicated no permanent changes.

More experimentation is needed to clarify discrepancies observed for certain types of devices.

The foregoing review of the damage in electronic piece parts exposed to nuclear radiation, pulsed or steady-state, has been very limited for various reasons, including scarcity of reliable information. In fact, one class of problem has been completely omitted, and that is activation of piece part materials. It is obvious that nuclear activation of materials in piece parts could cause problems over and above either interrupted operation or actual failure For instance, the creation of a long-lived isotope could prevent the repair of these electronics for long periods of time. A case in point is the use of kovar

Fig. 7: A magnesium oxide radiation detector for testing use.



in tubes. This alloy contains cobalt which, when activated, produces the cobalt-60 isotope—a very hot material with a long half life. Problems of this type are being studied in a Signal Corps contract with Stevens Institute of Technology.[12]

At present, the Radiation Effects Information Center (REIC) at Battelle Memorial Institute, Columbus, Ohio, has been designated by the Department of Defense (DOD) as the information collation agency for work covering pulsed radiation effects on electronics. This group has published a number of general reports on the effects of nuclear radiation. In the future, REIC plans to issue a handbook on nuclear effects information for electronic equipment designers. This book will be a working tool. It will be modified in time to include more information as it becomes available.

Fig. 8:

Radiation Levels Outlined in MIL Standard 446A

ENVIRONMENTAL CHARACTERISTICS	GRP. IV	GRP. VI	GRP. VIII
Nuclear Radiation (Reactor)			
Neutron Flux Level (Fast, E> 10 Kev.)			
Intensity, n/cm²-Sec	NA	10^{10}	10^{10}
Time, Hours	NA	1,000	1,000
Gamma Flux Level			
Intensity, R/hr	NA	5×10^5	5×10^5
Time, Hours	NA	1,000	1,000
Thermal Neutrons		*****	*****
Nuclear Radiation (Pulse)			
Neutrons (Fast, E> 10 Kev.)			
Total Dose, n/cm²	10^{13}	10^{13}	NA
Duration, Half Amplitude, Sec.	5×10^{-6} to 5×10^{-2}	5×10^{-6} to 5×10^{-2}	NA
Gamma			
Peak Intensity, R/Sec.	10^8	10^8	NA
Duration, Half Amplitude, Sec.	$<10^{-5}$	$<10^{-5}$	NA

**** Thermal Neutrons are not listed as a requirement but, since all neutron fluxes have some thermal component, this component should be measured and reported with all tests. In no case should the total thermal neutron dose exceed the fast neutron dose by more than a factor of ten.

Problems Connected With Evaluation

The main problem to an investigator evaluating nuclear effects on piece parts is the scarcity of valid information. This scarcity is due to a severe lack of exposure facilities in the past. Also, the geographical location of most of the existing pulse radiation facilities, and the inherent hazards of the radiation environment, create many difficulties which are not found in similar environmental laboratory-type experiments. A brief review and description of the pulse radiation facilities which are being used are given below.

Sandia Pulse Reactor Facility (SPRF): The SPRF, located at the Sandia Corp., Albuquerque, N. M., is a reactor similar to the Godiva II which was used for radiation effects experiments at the Los Alamos Scientific Lab. In fact, the SPRF reactor is identical to the Godiva II except that increased reactivity is available, and additional safety factors have been added.

TRIGA—Mark F (General Atomic): Several TRIGA reactors are in operation in addition to the TRIGA facility at General Atomic, Torre Pines, Calif. These reactors are located at Diamond Ordnance Fuze Lab., Washington, D. C.; Armed Forces Radiobiology Research Institute, Bethesda, Md.; and Norair Div. of Northrop, Hawthorne, Calif. The TRIGA reactor produces high integrated neutron doses. However, because of its millisecond pulse width, it is not useful for all electronic piece parts and equipment.

KEWB Reactor (Atomics International (AI) Div. of North American Aviation): The KEWB reactor is located at Conoga Park, Calif., and was developed by AI. The KEWB pulse width is in the millisecond region and, therefore, the integrated neutron doses are high. However, the use of the KEWB is not feasible for short pulse width type effects experiments.

White Sands Missile Range Godiva II Reactor: This reactor is to be constructed at the WSMR, and will be a type similar to the Sandia reactor. The reactor will be used for specific types of missile electronics evaluation programs.

Linear Accelerators: Several Linacs are available for short pulse width type radiation effects experiments. These Linacs are located at Rensselaer Polytechnic Institute, Troy, N. Y. (45 Mev); Hughes Aircraft, Fullerton, Calif. (10 Mev); General Atomic, Torre Pines, Calif. (45 Mev); and WSMR (10 Mev).

The large use factor planned for the various facilities, and their location in the western part of the U. S., has led to consideration of more facilities, mainly for advanced Godiva-type reactors. These would be capable of producing neutron outputs one to two orders of magnitude above those of conventional Godiva-type reactors, and at shorter pulse widths. These include:

Army Pulse Reactor—Aberdeen (ARPA): This facility, proposed to be located at Aberdeen Proving Ground, Aberdeen, Maryland, would be mainly for use by the Army Ordnance Corps, Army Chemical Corps, and the Signal Corps, as well as by electronic component manufacturers located within a 200-mile radius of Aberdeen Proving Ground.

Proposed New York State Pulsed Reactor: The State of New York, in cooperation with a number of manufacturing groups in that State, are now studying the possibilities for use of a pulsed reactor of the beyond-Godiva type. A consultant engineering firm has been employed to complete the study and make recommendations for a facility, which will be partially financed by the State of New York.

General Electric Company Reactor: The General Electric Co. has been studying the possibility of constructing a beyond-Godvia pulsed reactor for use in their radiation effects program, and for general use by other electronic equipment contractors. No definite decision has been reached to date as to the location of such a facility.

Radiation Effects Mobile Lab (REML)

From the description and location of the presently available facilities, the varied exposure requirements and the long delay expected in obtaining the planned reactors, it becomes evident that the piece parts electronic monitoring equipment associated with this program must be made completely mobile. Also, the equipment must be shock-mounted to withstand transportation environments for multi-thousand mile trips. The equipment must also be completely reliable, since limitations in on-site pre-experimental time virtually preclude the possibility of trouble shooting equipment malfunctions at the site. An example of the type of fully equipped vehicle which is being used in radiation effects experiments by the Signals Corps is shown in Fig. 5. This particular trailer, referred to as the Radiation Effects Mobile Laboratory, is one of the most complex instrumentation vehicles now in use. With the instrumentation in the REML, it is possible to monitor 90 channels of dynamic information at one time. This instrumentation system is needed because of the large number of devices which are exposed during each experiment. The number of devices is predicated on the minimum sampling of devices which will provide statistically valid information.

To determine the effects of nuclear radiation on a single component, such as an electron tube or transistor, etc., all associated circuitry must be completely shielded from the radiation field. The intense radiation fields from a pulse reactor necessitate that extreme precautions be taken to preclude effects on monitoring equipment and associated circuitry. Transient effects noted during some early field experiments at pulsed nuclear reactors were later found to be attributable to the effects of an air capacitor oscillator, which was part of the instrumentation equipment. Extreme care must be taken to eliminate all extraneous phenomena, such as cable effects and air ionization, which cause shunt leakage, etc. The latter effect can be reduced by potting the test chassis with paraffin or other solid dielectrics, as shown in Fig. 6, or by immersing the sample in oil.

Dosimetry is also an area in which deficiencies exist. The radiation levels to which a device is exposed must be known before any correlation or analysis is possible. Many times it is impossible to determine the dose or dose rate at the exposure sample and, therefore, only mean values are available necessitating extrapolation which adds more errors. Dosimetry is rapidly advancing, and devices such as the Magnesium Oxide Radiation Detector (MgO-RAD), developed by one of the authors (R. G. Saelens), and shown in Fig. 7, as well as the SEMI-RAD, developed by Dr. S. Kronenberg and Mr. H. Murphy of USASRDL, are helping to alleviate some of these problems.

Difficulties have also arisen in correlating transient changes in electron device operation to the type of incident radiation, i.e., neutron and gamma. The size of many detectors precludes measurement of radiation levels at the same position as the exposure sample and, therefore, one must extrapolate to find the exact dose level to which the part has been exposed.

It should be mentioned that gamma as well as neutron radiation effects must be considered. The cause of transient radiation effects on many components has been attributed to gamma radiation. Accurate and dependable data about damage caused by gamma radiation on piece parts are scarce. However, work is now being stressed on materials effects, and further tests on piece parts are planned. In general, it can be said that the damage threshold for piece parts ranges from 10^4 to 10^8 R/sec.

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Reliability of Electronic Systems

The Signal Corps Laboratory is approaching the nuclear environment problem in a manner similar to that used in solving the high shock and vibration problems of the early fifties. After much effort, it was learned that the best approach to high shock and vibration environment reliability was to first learn the capability of the individual piece parts. Later this information on parts was extrapolated into an equipment or black box capability. At this time, new problems pertaining to the equipment itself appeared. For example, resonances occurred in the main structural members of the equipment itself, which caused large g levels to be transmitted to the piece parts, resulting in early failure. Since no structure could be made absolutely resonance-free and serve the other purposes for which it was intended, compromises were necessary. On the one side, attempts were initiated to reduce the occurrence and intensity of the resonance, and on the other hand to harden the piece parts to the enhanced environment. The success of this approach has been documented, and it is now in general use.

Standardization

To insure a successful program for the development of radiation-resistant electronic components, a standard must be established by which all electronic parts and systems can be measured. Since the electronic piece part is the basic building block in systems reliability, if criteria are established for the piece parts, then the equipment designer must carry through under the same standard. DOD is aware of this need, and a preliminary standard has been prepared for the guidance of military electronic designers. This document, known as MIL-STD 446, was prepared in April 1959, and revised in November 1960 as MIL-STD 446A. It is under the cognizance of the Armed Forces Supply Support Center, Washington 25, D. C.

The express purpose of this document is to establish uniform environmental design requirements for use in planning of R&D programs, and to provide a guide for use in the preparation of military specifications and standards involving electronic parts, tubes, and solid state devices. This standard has been approved by DOD, and is mandatory for use in R&D. Fig. 8 shows the nuclear environmental requirements as indicated in the MIL-STD 446A. Categories shown are defined in the document as follows:

Group IV covers that group of electronic parts, tubes, and solid state devices for use in electronic equipment of high performance aircraft and surface-to-air and air-to-air missiles.

Group VI covers that group of electronic parts, tubes, and solid state devices for use in electronic equipment of nuclear powered aircraft and ballistic missiles.

Group VIII covers that group of electronic parts, tubes, and solid state devices for use in electronic equipment of nuclear powered weapons.

Standardized paragraphs cover the measurement of the nuclear environment, and the criteria of failure are also included in MIL-STD 446A.

Conclusion

It is apparent from the foregoing that a large and growing effort has been mounted by DOD to harden, for certain specialized applications, electronic systems for the nuclear environment. The program has now reached a point which shows much progress and excellent planning toward achieving the end goals. The expanding work now requires the inclusion of many other commercial electronic development and research organizations. Without a doubt, most of those which have not been involved in this problem to date will be exposed to it shortly. Unless preparations are made now, these companies will find themselves badly handicapped in responding to the growing DOD nuclear environment requirements.

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